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Comparisons of Long-Term Trends and Variability in the Middle Atmosphere

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Introduction

The USU Rayleigh Lidar (41.74°N 111.81°W) has been regularly used to measure temperatures in the middle atmosphere from 45 to 90 km. It is well suited for nightly observation; provides excellent vertical temperature resolution; and does not need external calibration. It began operation in August 1993 and a dataset spanning more than ten years has been collected. The analysis here includes 593 nightly temperature profiles from September 1993 through July 2003.

With many sources of variation in the atmosphere, all temperature effects cannot be easily detected. The largest source of temperature variation, and the easiest to measure, is the annual variation. Other effects, such as the semiannual variation, solar cycle radiation, and secular trends are also important but more difficult to detect at every altitude. Our model includes these effects, some of which are significant at some altitudes while others are not. The linear model used in this analysis included variables for the annual and semiannual variations, solar effects, average temperature, and secular trend. The MgII index, averaged over 81 days, was used as a solar proxy instead of F10.7 because it yielded a marginally better fit.

Method

A least squares method was used to determine the coefficients for the following linear model:

$$T(t) \;=\; \overline{T}(z) + A_0(z)\cdot t + A_1(z)\cdot MgII + A_2(z)\cdot\cos(2\pi t)$$
$$A_3(z)\cdot\sin(2\pi t) + A_4(z)\cdot\cos(4\pi t) + A_5(z)\cdot\sin(4\pi t) + T'(t,z),$$

where t is the time measured in fractions of years from September 1993; $\overline{T}(z)$ is the average value of the temperature at altitude z; $A_1(z)$ is the response to the MgII proxy; $A_2(z)$ and $A_3(z)$ are for the annual term, and $A_4(z)$ and $A_5(z)$ for the semiannual term; $A_0(z)$ is the temperature trend in K/year; and $T'(t,z)$ is the temperature perturbation due to uncertainty and other effects.

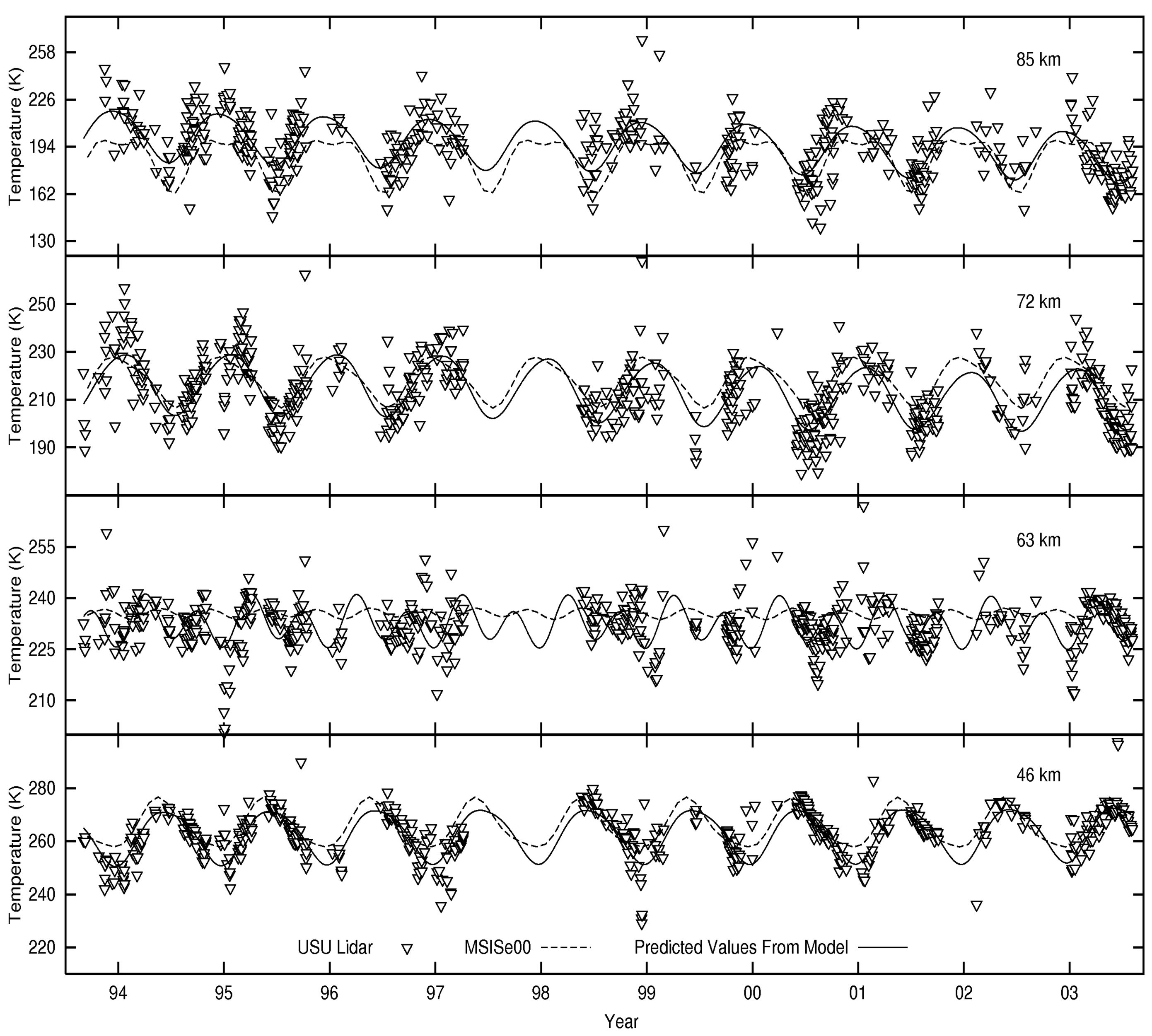

Figure 1: Time variation of temperature at selected altitudes.

Typically confidence intervals are calculated with the assumption that the errors are independent, have identical distributions, and are normally distributed. It was found from the analysis that these assumptions held at only a few altitude bins. Consequently, in order to obtain accurate error bars, a bootstrap method called residual resampling was used. The method is basically this. It is assumed that a residual at one point could have easily occurred at any other point. The model is fitted using typical least squares, and predicted values are generated from the model. The residuals are then randomly added, with replacement, to the predicted values and the model is fitted with the new data. This process is iterated (5000 times in this analysis) and distributions of the coefficients are generated. From these distributions, two standard-deviation uncertainties (about 95%) are calculated. The resulting confidence intervals are free from the assumption that the errors are normally distributed.

Results

Figure 1 compares the USU lidar data to the MSISe00 empirical model and to the predicted values from the linear model. An annual variation dominates at the highest and lowest altitudes (but is shifted by almost 6 months), whereas the semiannual variation is most prominent in the middle altitudes. In addition, between 85 and 73 km a very clear cooling trend is present in the data and the fit. This is easily seen when compared to the MSISe00 temperatures. Below 67 km there is no significant warming or cooling trend.

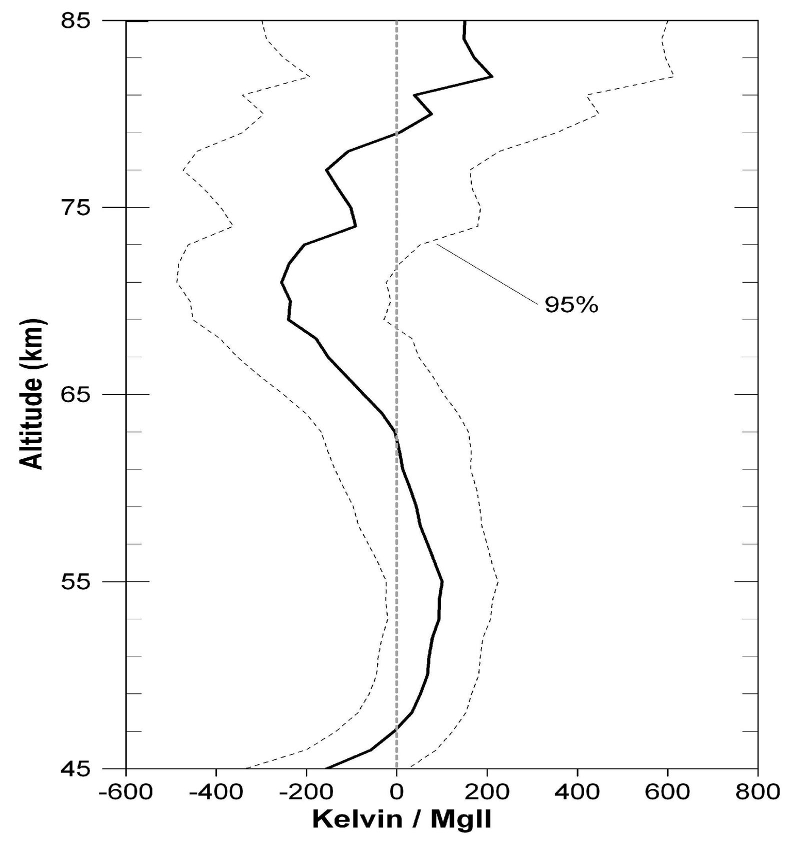

Figure 2: Temperature response to solar irradiance.

Figure 2 shows the solar cycle effect in K/MgII plotted with altitude. The greatest response to solar irradiance is at 71 km, -255 K/MgII. The MgII index varied from 0.2639 to 0.2845 over the solar cycle, which gives a maximum temperature fluctuation of 5 K. This is the only altitude where a significant solar cycle effect was detected, and it is negative. At other altitudes this effect is much smaller.

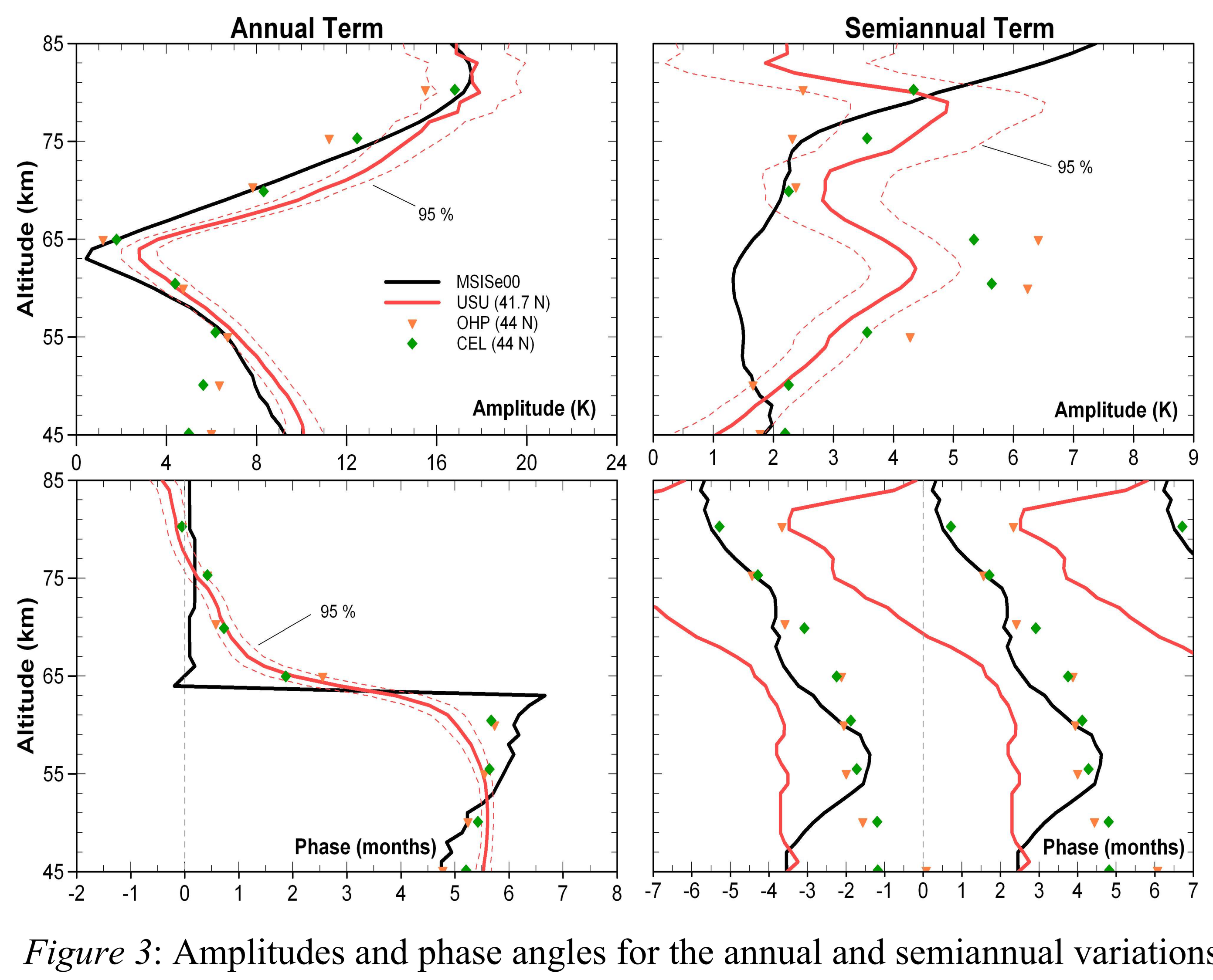

Figure 3: Amplitudes and phase angles for the annual and semiannual variations.

Figure 3 is a comparison of amplitudes and phase angles for the annual and semiannual variations from four datasets: USU, MSISe00, and two French lidars, CEL and OHP. (It should be noted that OHP and CEL are only 550 km apart and at the same latitude.) The amplitudes and phase angles for MSISe00 were extracted using the least-squares curve fitting algorithm. Our analysis shows that the annual and semiannual variation are statistically significant at every altitude range.

Between 55 and 80 km the amplitudes for the annual terms generally agree, with the USU data being about 3 K warmer. Below 55 km the amplitudes from the two French lidars are cooler by about 4.5 K. The phase angles for the annual oscillation from these four datasets are very similar throughout the altitude range (except for the unrealistically rapid phase change in the MSISe00 model).

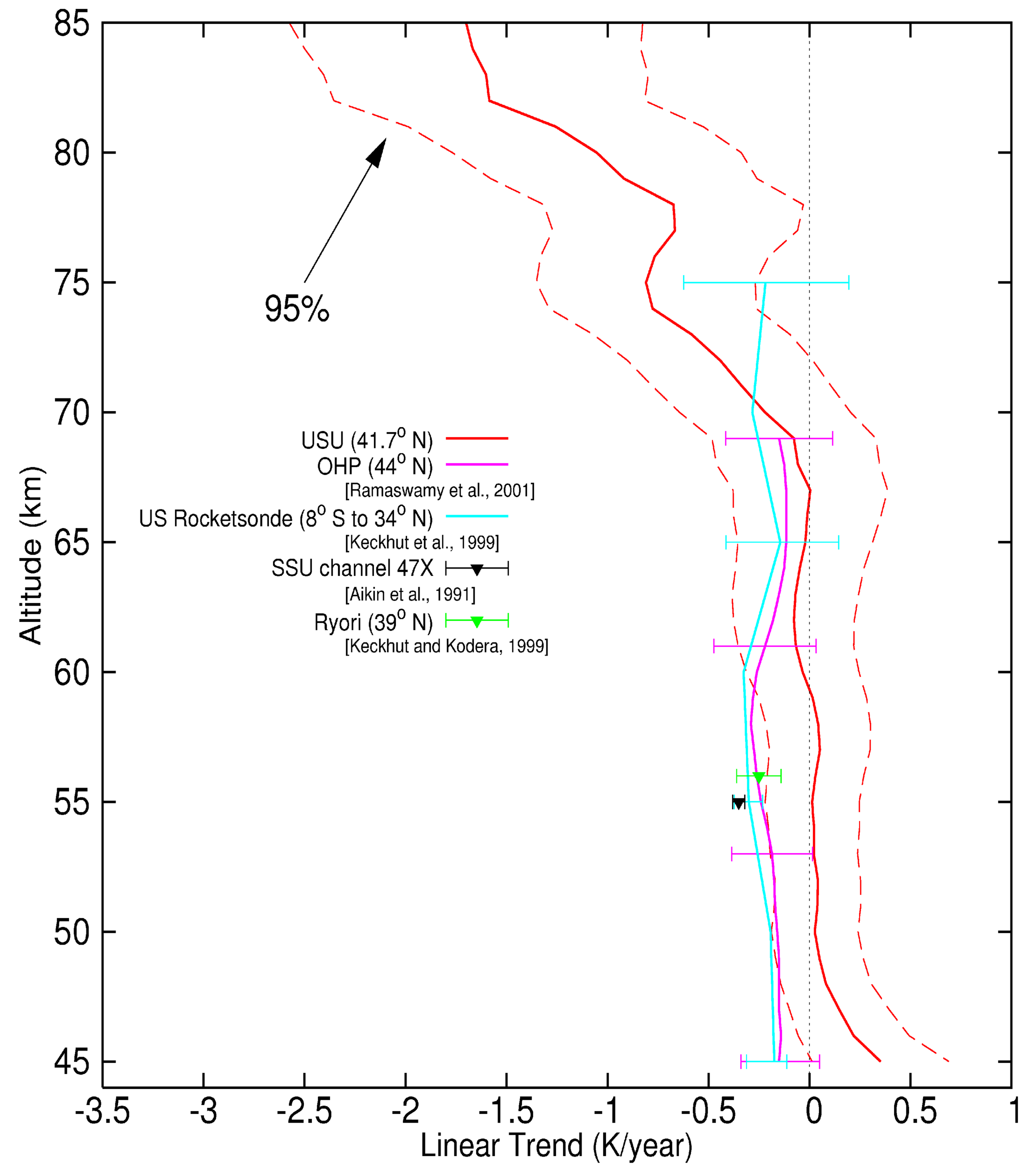

Figure 4: Linear temperature trends.

For the semiannual oscillation there are large differences between the four datasets. In amplitude, the USU and French data have similar profiles at high and low altitudes, showing the smallest values where the amplitude of the annual oscillation is the greatest. However, the MSISe00 amplitudes are significantly different. In phase, the USU data differs greatly from the others. At 65 km the French results lag by 2 months, but at 82 km they shift and lead the USU data by 0 to 2 months.

Figure 4 shows the variation of the linear temperature trend with altitude. This figure also shows the results of temperature trends from other groups at similar latitudes. They are in general agreement below the 70 to 75 km range, where there is no significant cooling at the 95% confidence levels. Above this the USU data shows a large cooling trend that increases with altitude, reaching -1.0 ± 0.7 K/year at 80 km.

Conclusions

- Except for a small cooling at 71 km no significant solar cycle variation was detected.
- A significant annual variation is found, which agrees in amplitude and phase with MSISe00 and the French lidars.
- A significant semiannual variation is found that has a profile similar to those of the French lidars, but differs substantially from the MSISe00 model. It disagrees in phase with the French lidars and the MSISe00 model.
- No cooling trend is found below 73 km, in general agreement with the other data shown. Above 73 km there is a significant and large cooling trend which reaches -1.0 ± 0.7 K/year at 80 km.
- Continued observations are needed to better measure the significance levels of the results and to determine if the large cooling trend will increase or diminish with time.

ACKNOWLEDGMENTS
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